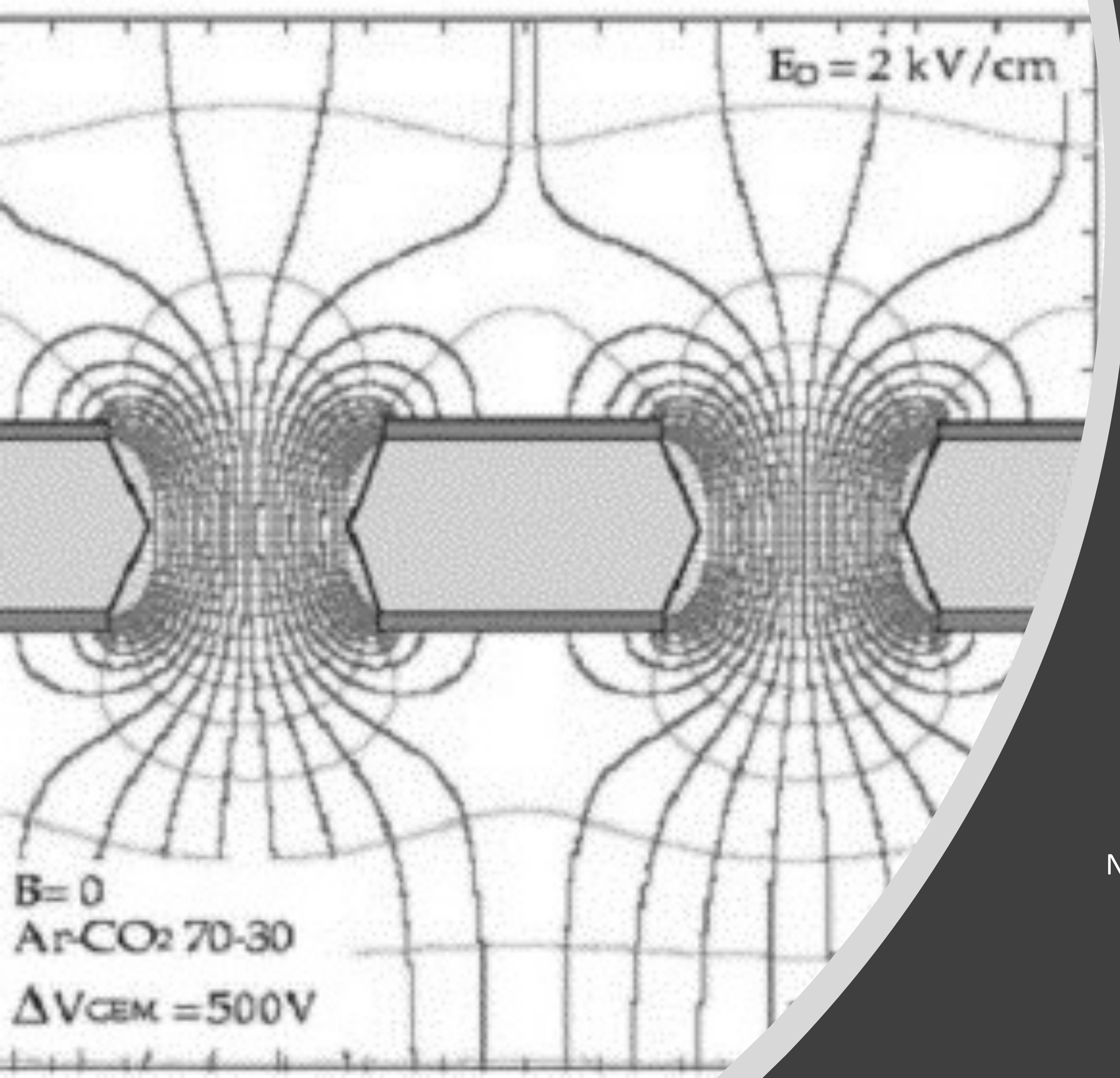


High-Pressure Gaseous TPCs

Jennifer Raaf (Fermilab)

July 23, 2022

Community Summer Study, Snowmass @ Seattle

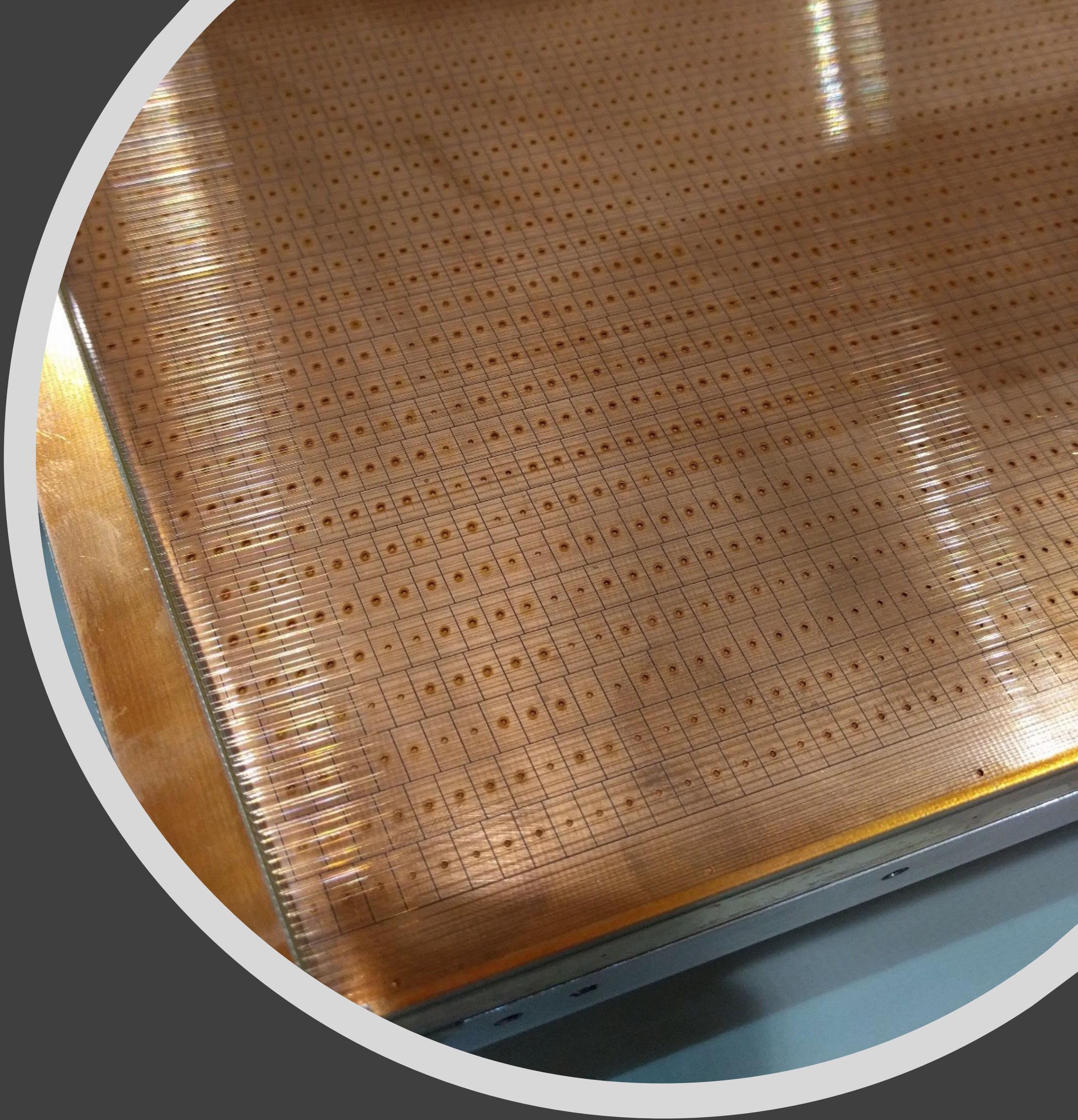
NF/IF Instrumentation for Neutrino Experiments

Gas detectors have been critical to particle physics measurements for many decades

- Fine spatial resolution & high rate capability
- Cost-effective way to instrument large areas w/low material budget
- Operate in magnetic field, rad hard

Gaseous TPCs now commonly used in rare event searches

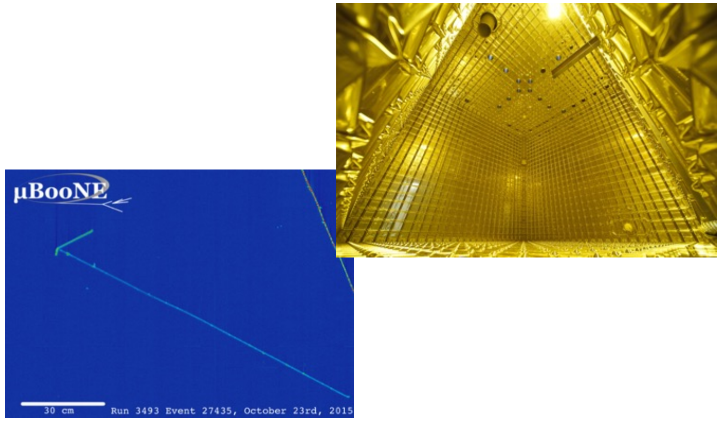
- Target material = detection medium
  - Flexibility to choose gas target (Ar, Xe, H_2, D_2…) and operating pressure
    - Higher pressure → more target material in the same volume
    - Lower pressure → longer track lengths
- Full 3D reconstruction capability
- Can dope with other elements to influence detector sensitivity/response



IF08 Noble Elements: Detector Technologies

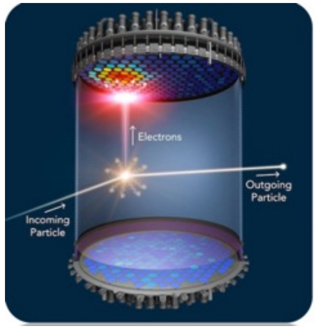
Neutrinos

- Single-phase Liquid Argon TPCs
- Dual-phase Liquid Argon TPCs
- High-pressure Argon Gas TPCs
- …



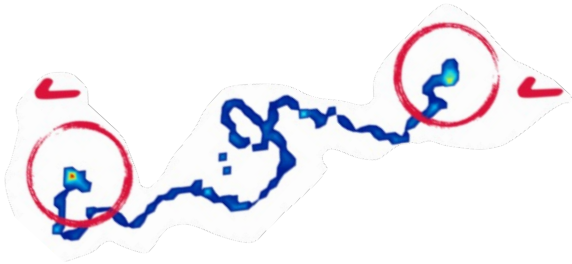
Dark Matter

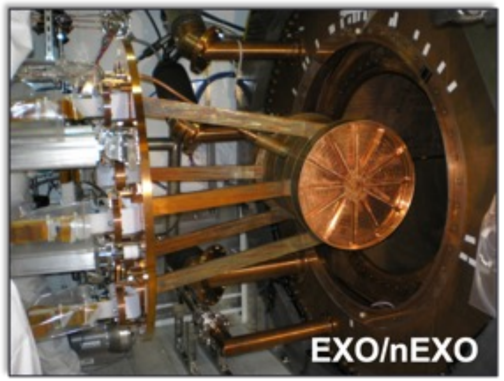
- Dual-phase Liquid Xe TPCs
- Dual-phase LAr TPCs
- Single-phase LAr
- Liquid Helium
- Noble Gas TPCs
- Liquid Argon/Xenon Scintillating Bubble Chambers
- …



0νββ

- Single-phase Liquid Xe TPCs
- High-pressure Xenon Gas TPCs





Instrumentation Frontier: Future Physics Needs

Neutrinos

- **Push energy thresholds** down to ~1 MeV to enhance oscillation physics, study supernovae νs, enable solar ν measurements, CEνNS…
- **Reduce background rates**
- **Scalability**
- **Unambiguous readout**
- …

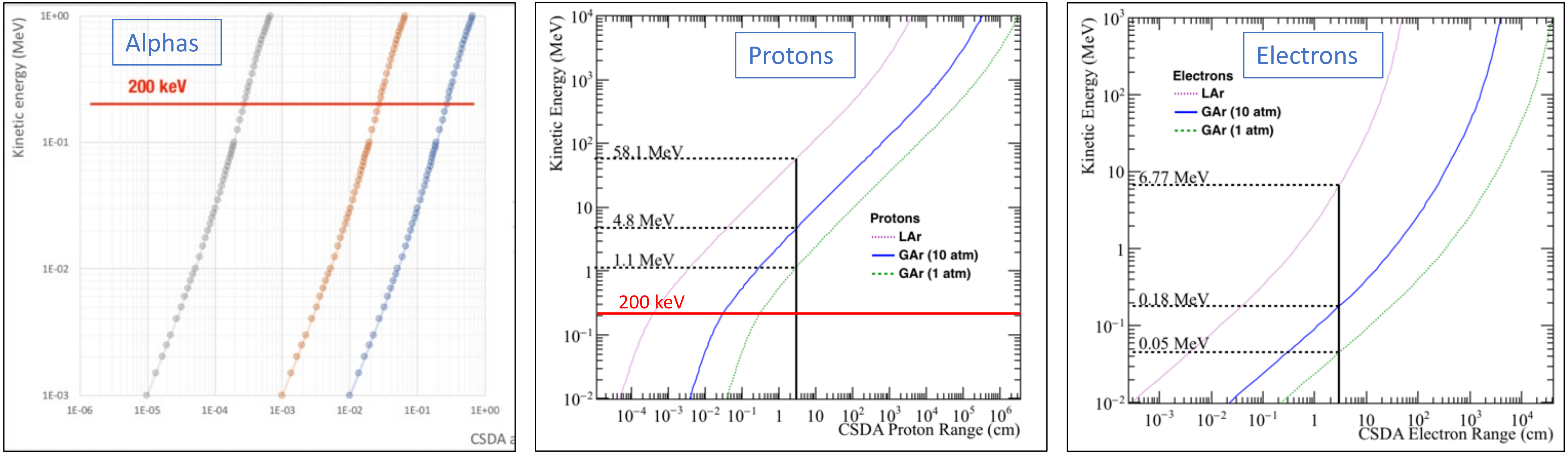
Dark Matter & CEνNS

- **Push energy thresholds** down to 1 meV/10 eV/ 1 keV to enable searches for low mass DM/1 GeV DM/WIMPs
- **Reduce background rates** (both intrinsic and external)
- **Extend calibrations to lower energy**
- **Scalability**
- …

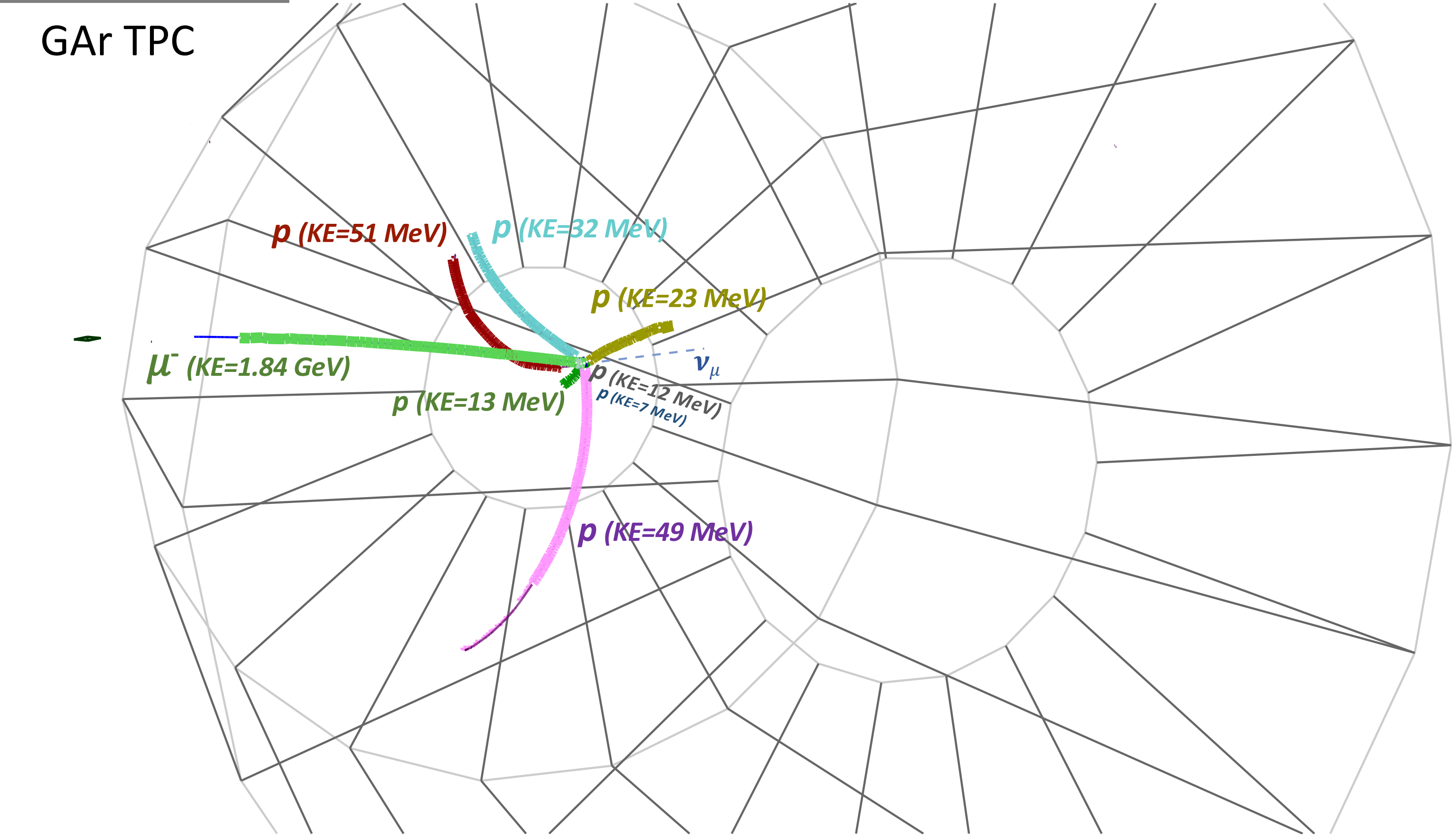
$0\nu\beta\beta$

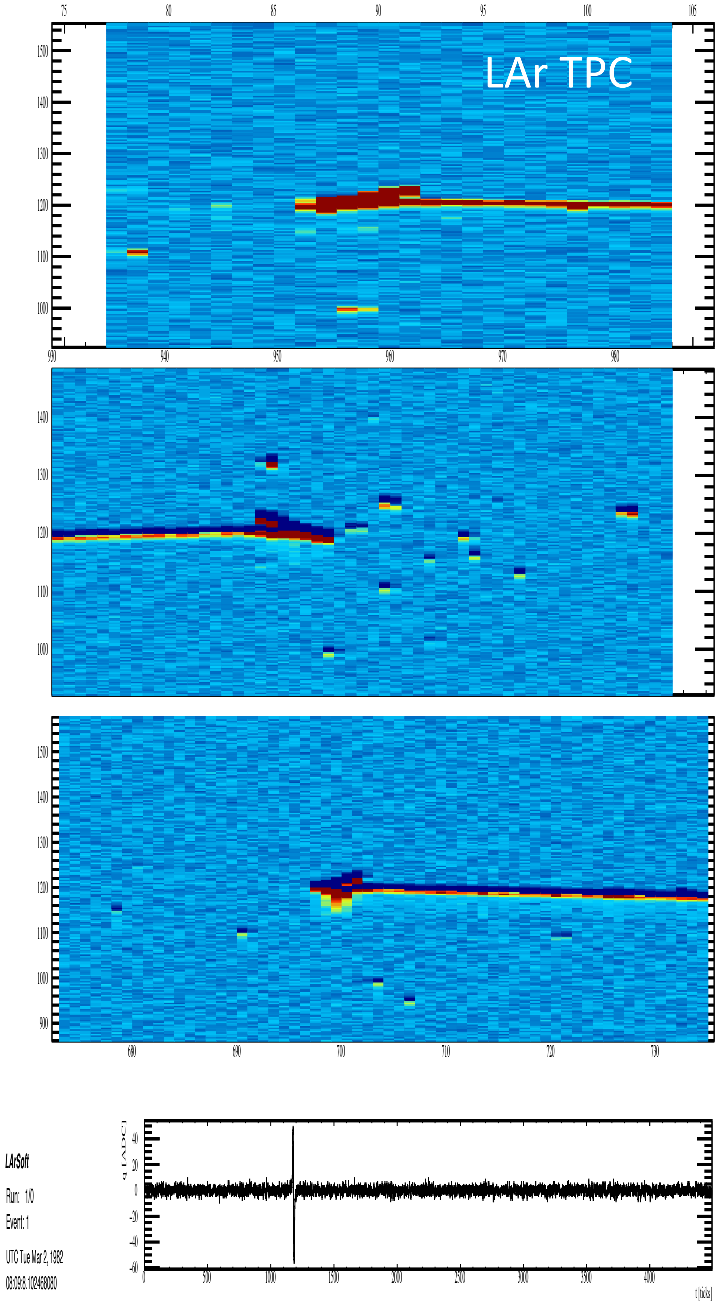
- **Improve energy resolution** to sub-% FWHM
- **Reduce background rates**
- **Scalability**
- …

Thresholds: detection → tracking



- Dark matter & 0nuBB experiments have much more strict requirements than neutrino experiments, but neutrino experiments will benefit from lower thresholds too
  - CEνNS, solar neutrinos, DSNB neutrinos, SN burst neutrinos, etc

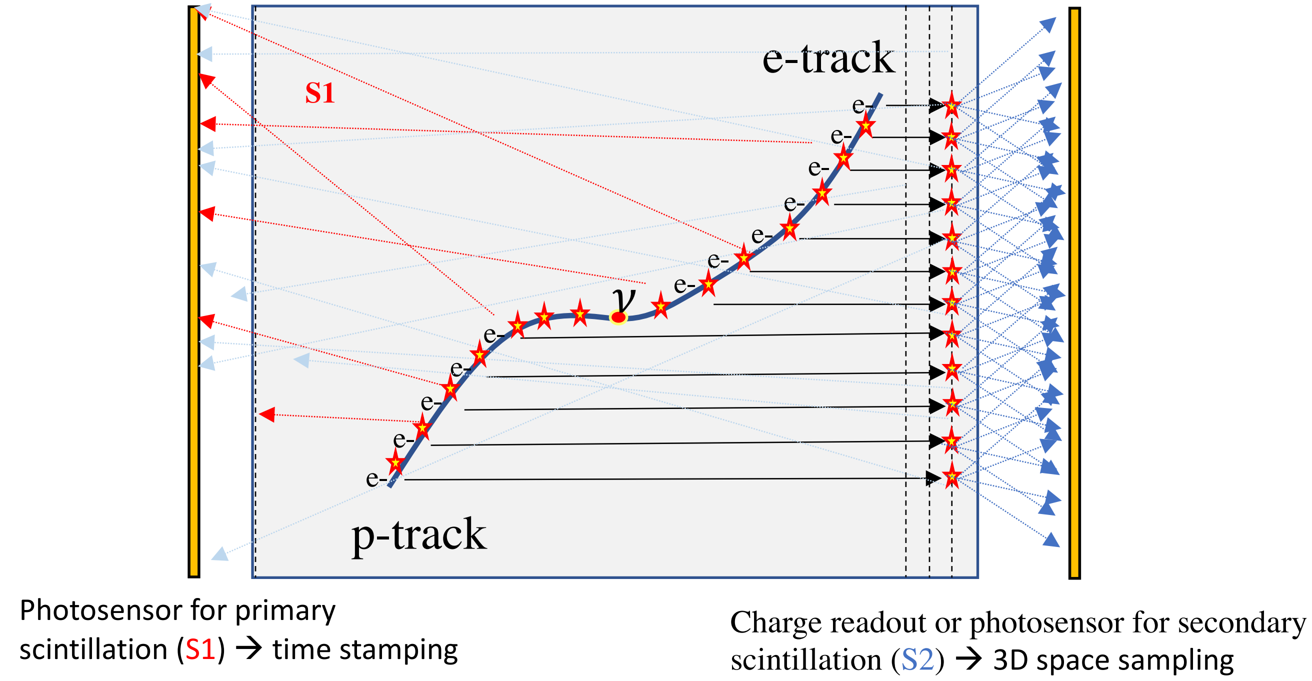


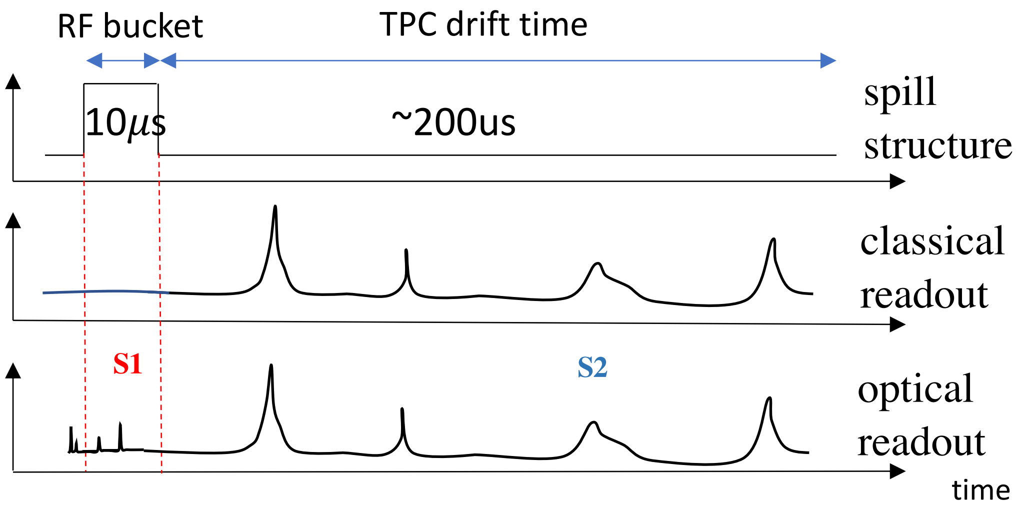


10 atm GAr vs. LAr: same neutrino event

- Neutrino interaction with 1 muon, 7 low energy protons, and 9 neutrons
- Lower density gaseous argon → particles travel further (and therefore easier to detect and reconstruct their tracks)

Detection channels

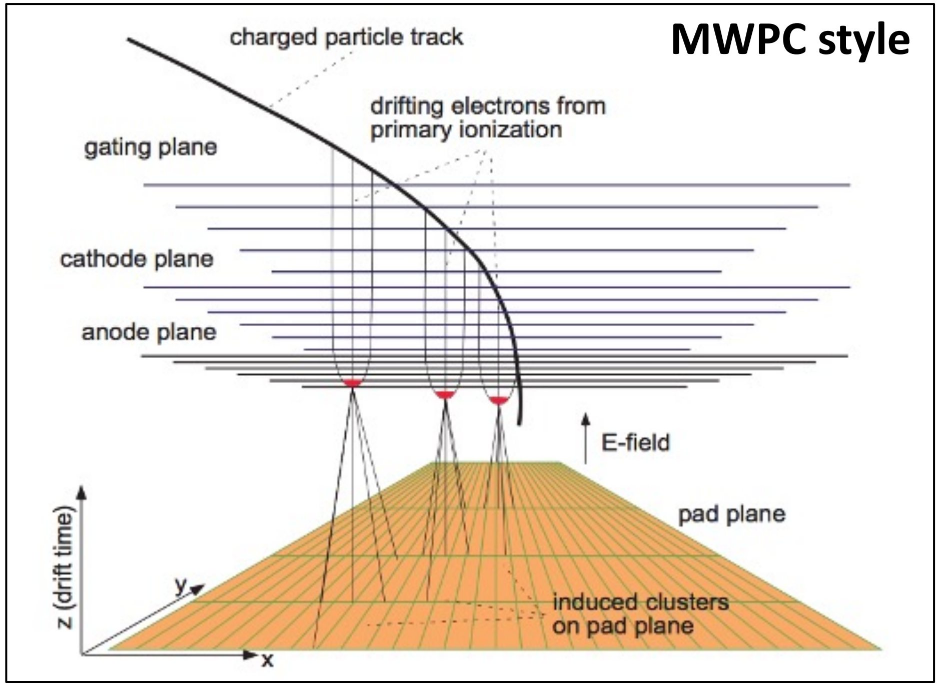


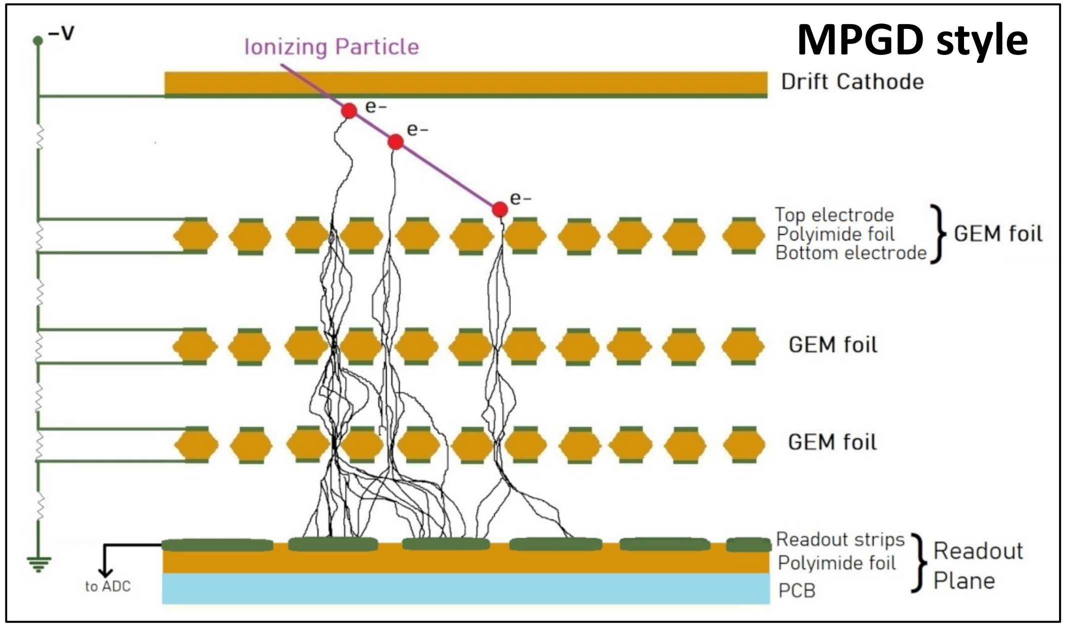


- Optical signal from primary scintillation light
  - Event t_0 tagging
  - Calorimetry
- Ionization signal: read out amplified charge or proportional optical signals
  - Tracking
  - Calorimetry

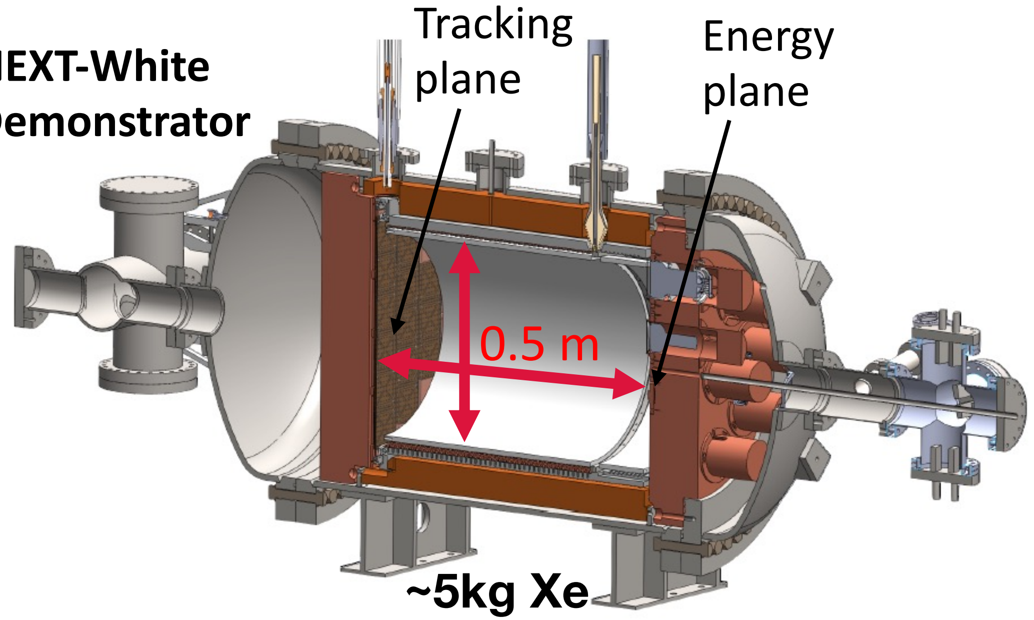
“Traditional” TPC readout

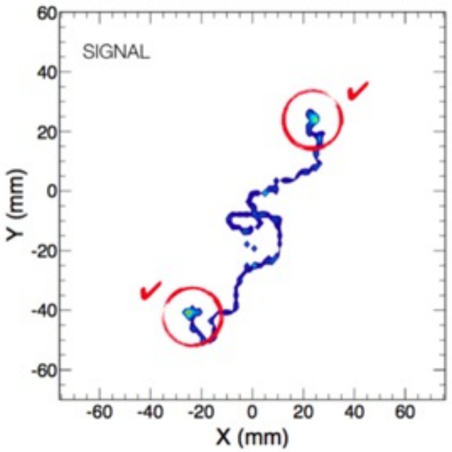
- Ionization charge amplification via avalanche gain in gas
  - Multi-Wire Proportional Counters (MWPCs)
  - Micro-Pattern Gaseous Detectors (MPGDs) → IF05
    - Gas Electron Multipliers (GEMs), Thick GEMs (THGEMs), Micromesh Gas Detectors (Micromegas), etc.
- Large gain improves S/N ratios
  - Achieving high gain can also mean operational instabilities (quenching S1 helps)
  - Can we find a gas that achieves good gain AND allows S1 detection?
- Good spatial resolution & dE/dx resolution
- Improvements for neutrinos & rare events:
  - Add light collection for t_0 tag → improved vertex resolution

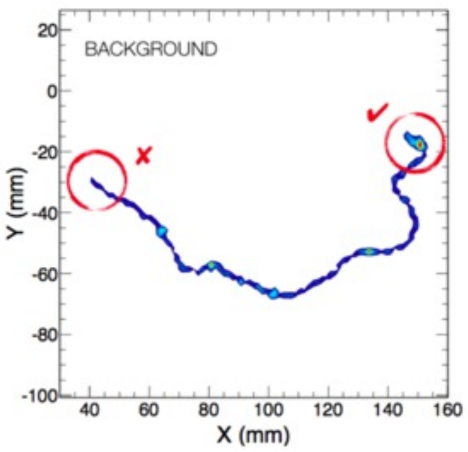


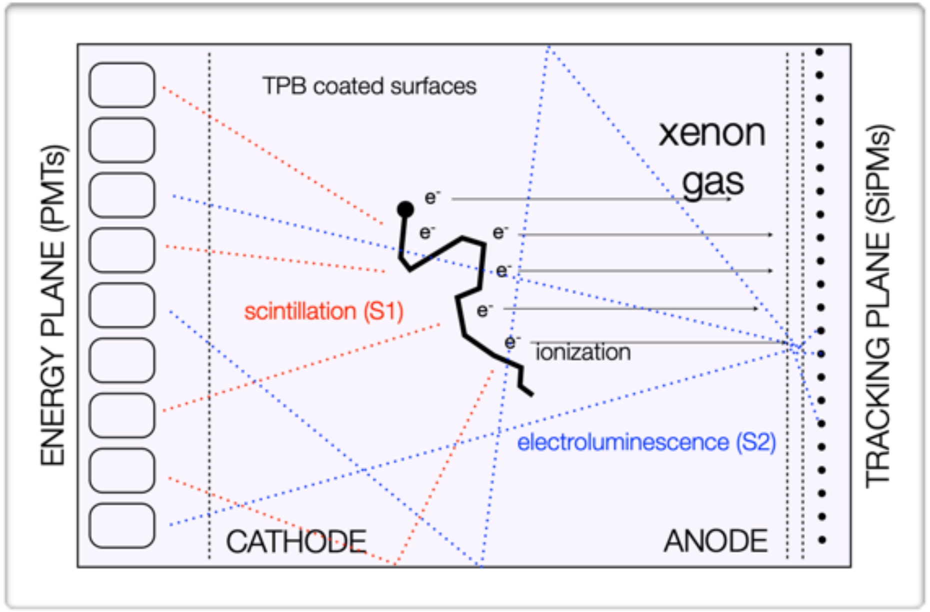


Light-based readout









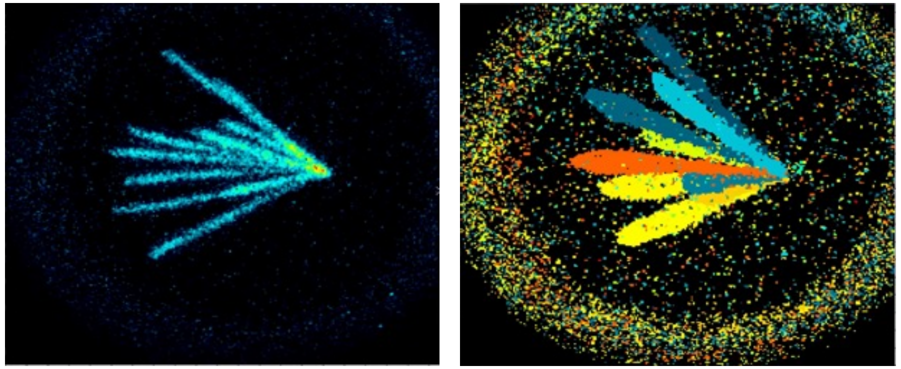
- High-pressure gXe TPC: 10 atm, S1 + S2 readout → energy + tracking
- Excellent energy resolution (~1%)
- Improvements will primarily come from:
  - **Scaling up to larger size**
    - Aim to move from 10kg demonstrator size to 100kg (NEXT-100), eventually to ton-scale (NEXT-1000)
  - **Background reduction**
    - Radiopure materials
    - Novel ideas: Barium tagging w/fluorescence

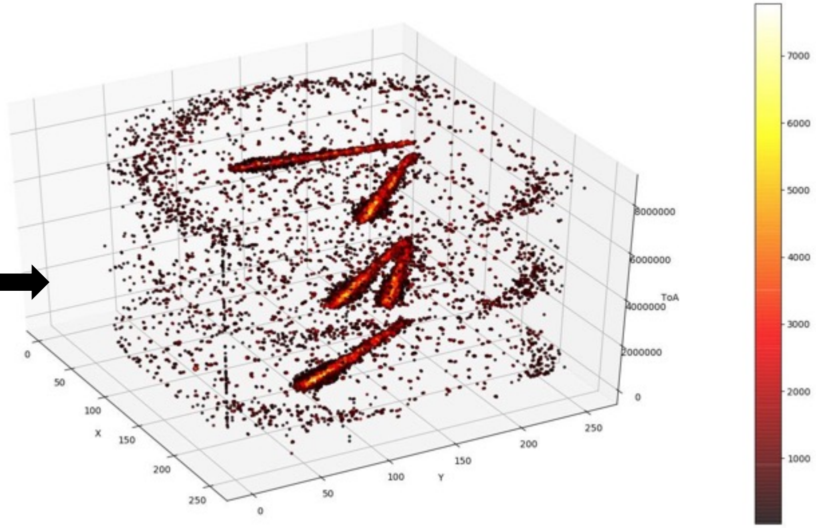
NEXT Collaboration, *JHEP* 10 (2019) 052 https://iopscience.iop.org/article/10.1088/1748-0221/14/06/P06001

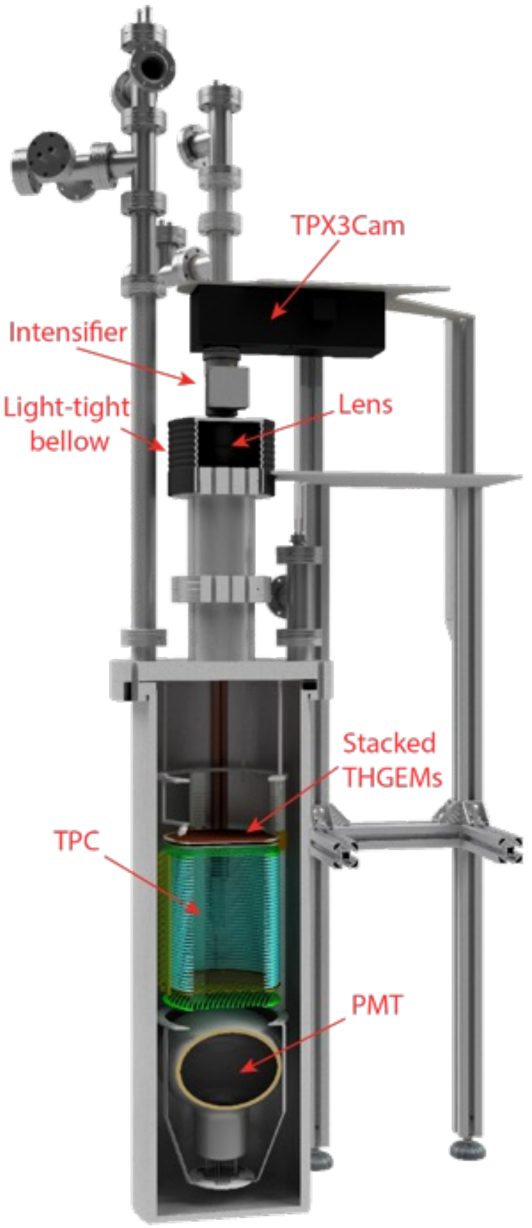
Light-based readout alternative

TPX3Cam

Time-over-Threshold Time-of-Arrival







- TimePix optical readout (K. Mavrokoridis/ARIADNE, Liverpool)
  - Initial demonstration & testing in gaseous TPC (100mb CF_4) w/dual THGEMs and Am-241 alpha source
  - Next step: demonstration at high pressure
- Potential benefits:
  - Reduced costs for large detectors?
  - Improvements in reconstruction fidelity

IF08 Key Messages

- **IF08-1:** Enhance and combine existing modalities (scintillation and electron drift) to increase signal-to-noise and reconstruction fidelity.
- **IF08-2:** Develop new modalities for signal detection in noble elements, including methods based on ion drift, metastable fluids, solid-phase detectors and dissolved targets.
- **IF08-3:** Improve the understanding of detector microphysics and calibrate detector response in new signal regimes.
- **IF08-4:** Address challenges in scaling technologies, including material purification, background mitigation, large-area readout, and magnetization.
- **IF08-5:** Train the next generation of researchers, using fast-turnaround instrumentation projects to provide the design-through-result training no longer possible in very-large-scale experiments.

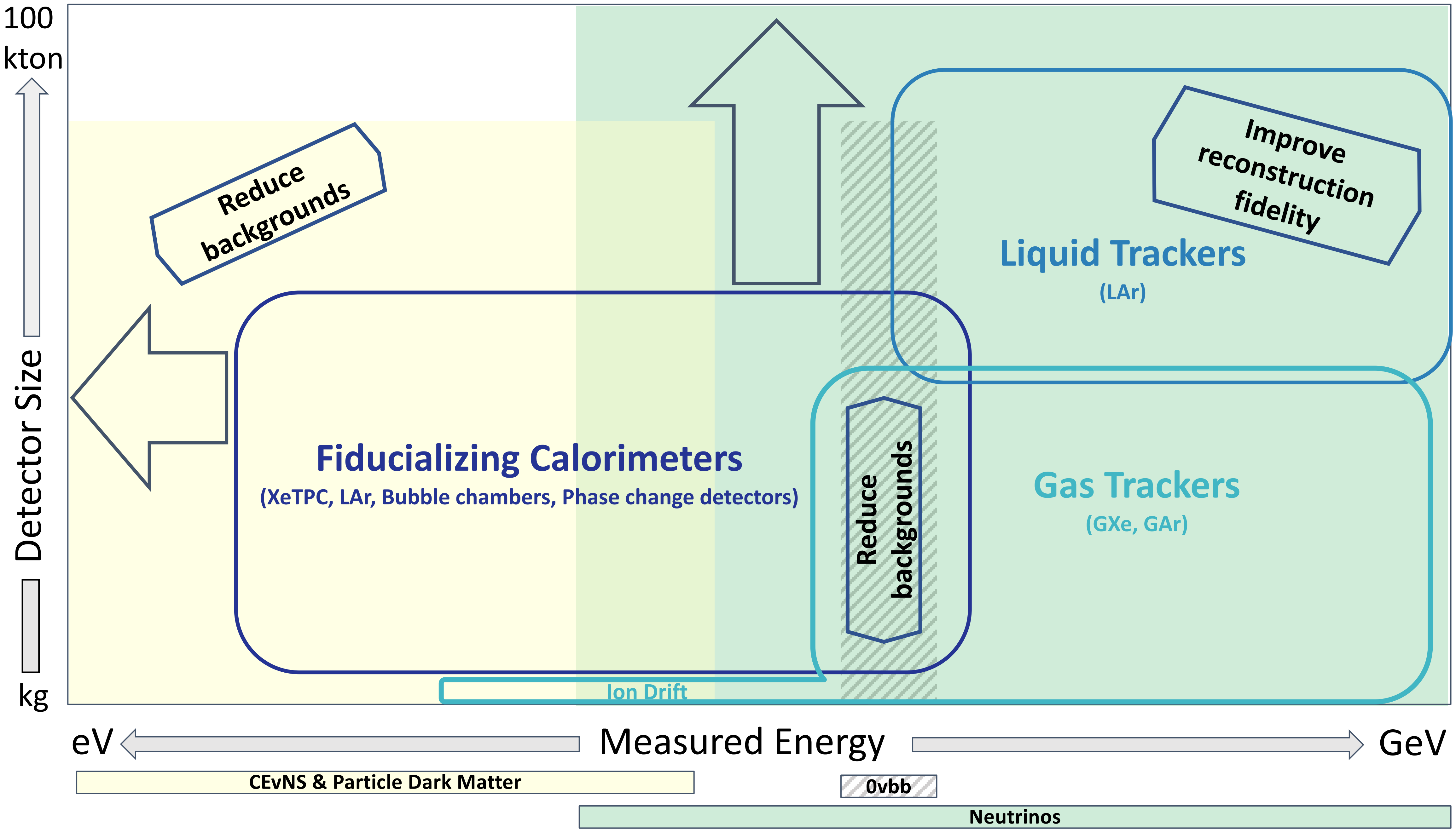
Summary

- High-pressure gas TPCs are an enabling technology for neutrino experiments (and rare event searches)
  - Improved tracking/reco capabilities → better control of systematics for DUNE
  - More physics! CEvNS, solar, SN nu, BSM searches
- Already commonly used in DM and 0nuBB
  - Neutrinos can take advantage of the many advancements that have happened thanks to past/ongoing R&D work in these areas
- NP/HEP would both benefit from joint development of these detectors

Extra Slides

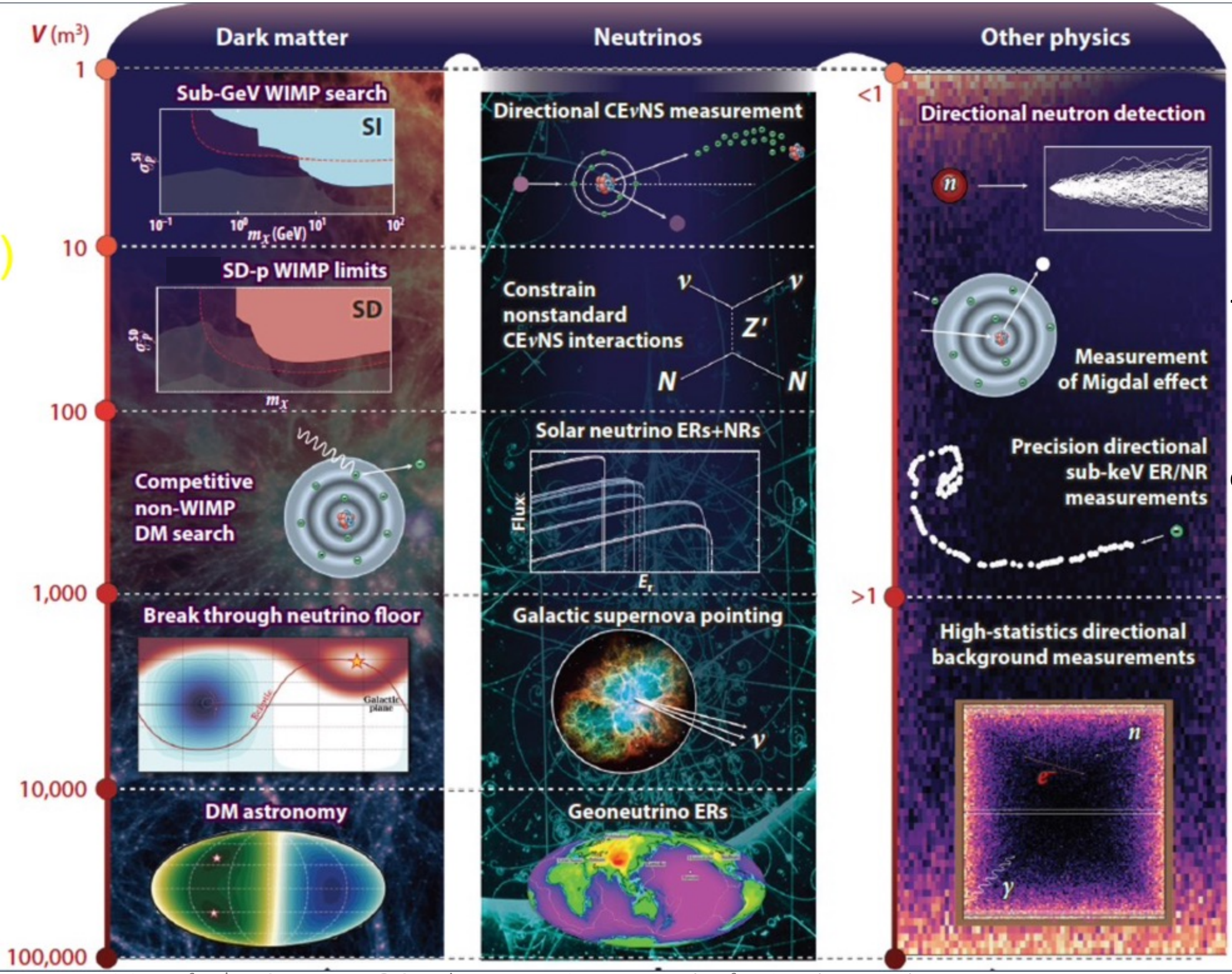
Connections

- Connections with:
  - IF05 Micropattern gaseous detectors (MSGC, GEM, THGEM, MICROPIC, MICROMEGAS, InGrid, etc)
  - IFXX Light collection: scintillation, ionization, near IR, VUV



100 kton
Detector Size
kg
Reduce backgrounds
Improve reconstruction fidelity
Liquid Trackers
(LAr)
Fiducializing Calorimeters
(XeTPC, LAr, Bubble chambers, Phase change detectors)
Reduce backgrounds
Gas Trackers
(GXe, GAr)
Ion Drift
eV
Measured Energy
GeV
CEvNS & Particle Dark Matter
0vbb
Neutrinos

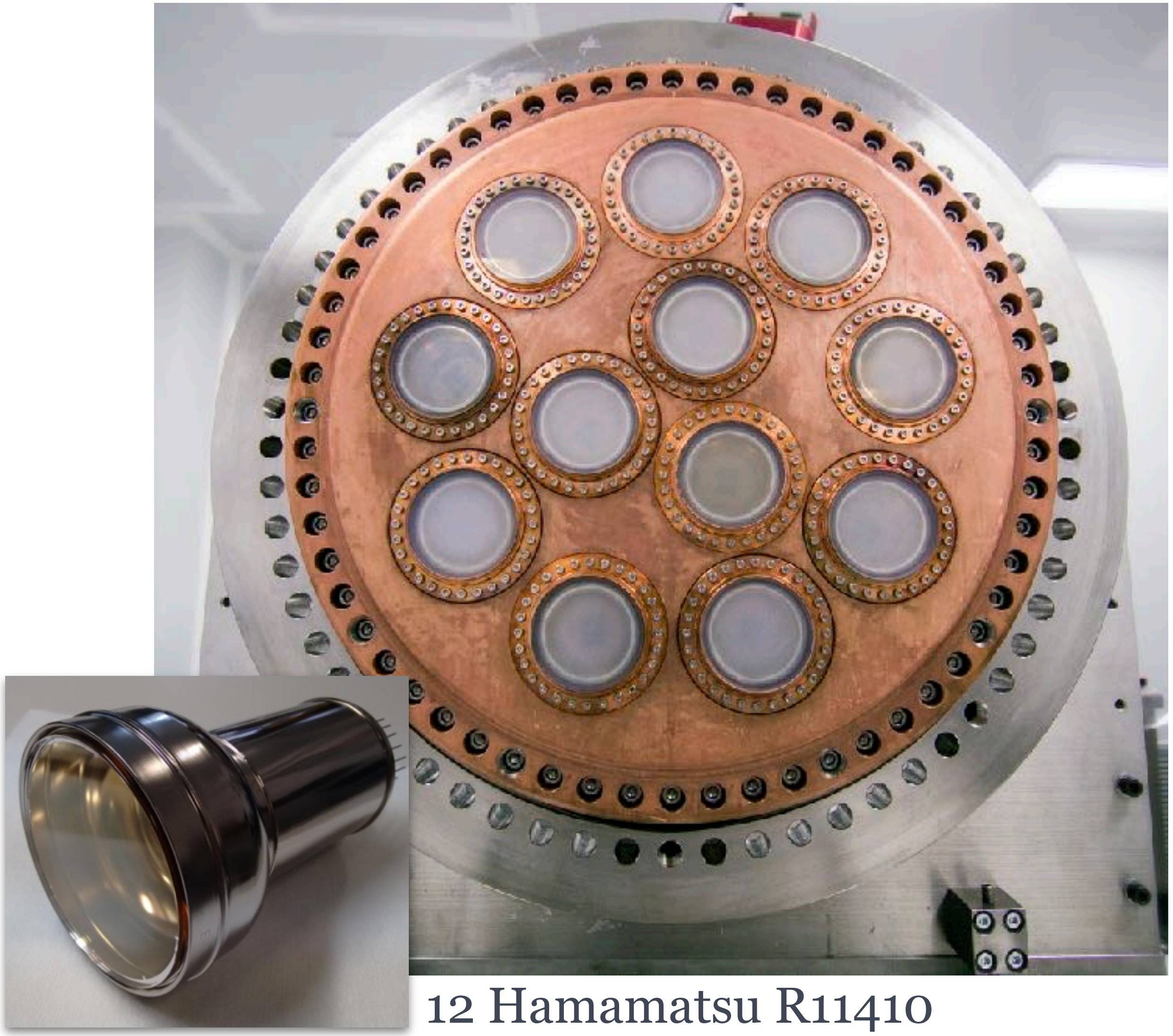
Physics opportunities with gaseous TPCs



https://arxiv.org/abs/2102.04596

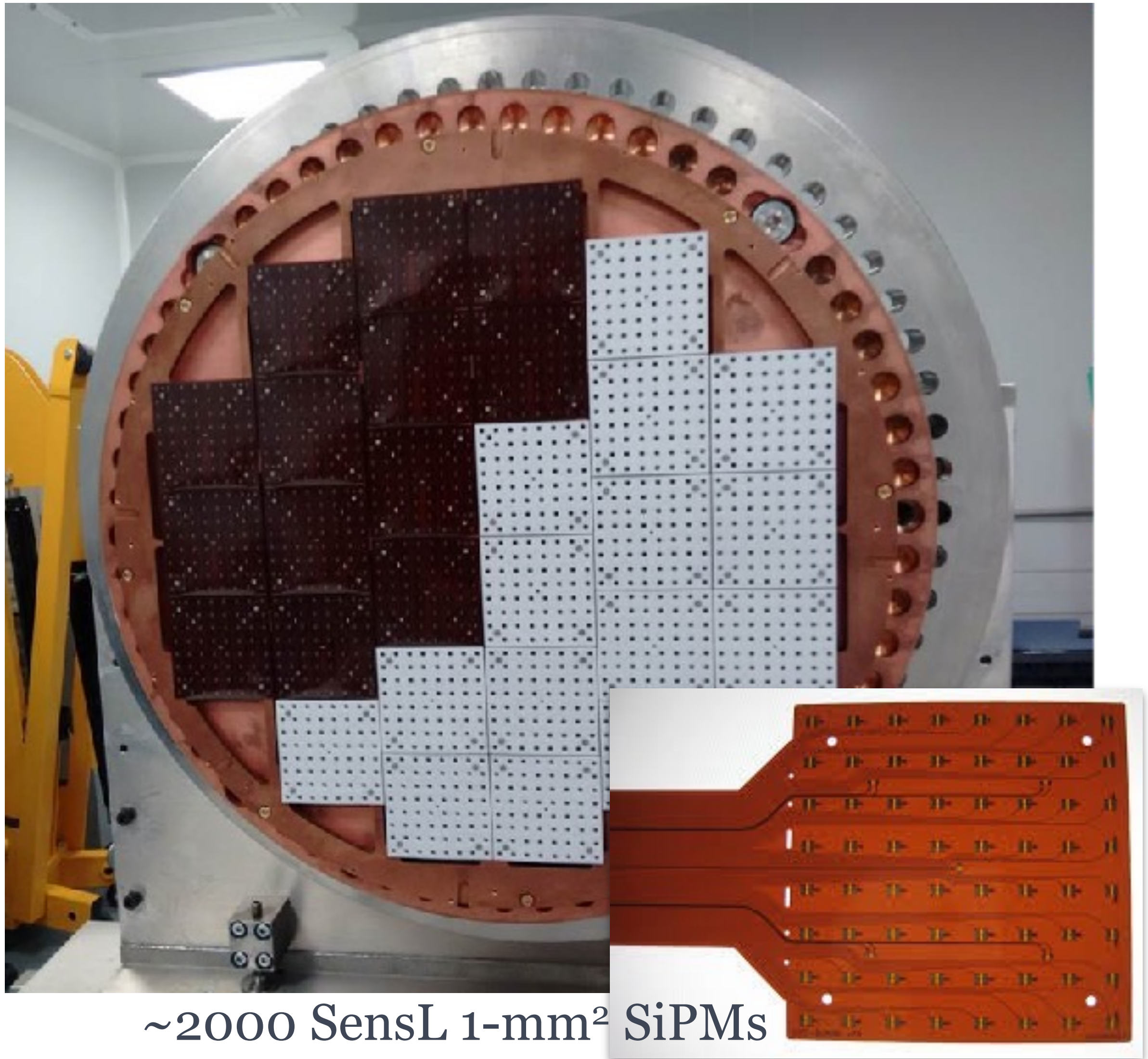
NEXT-White Readout

Energy plane



12 Hamamatsu R11410

Tracking plane

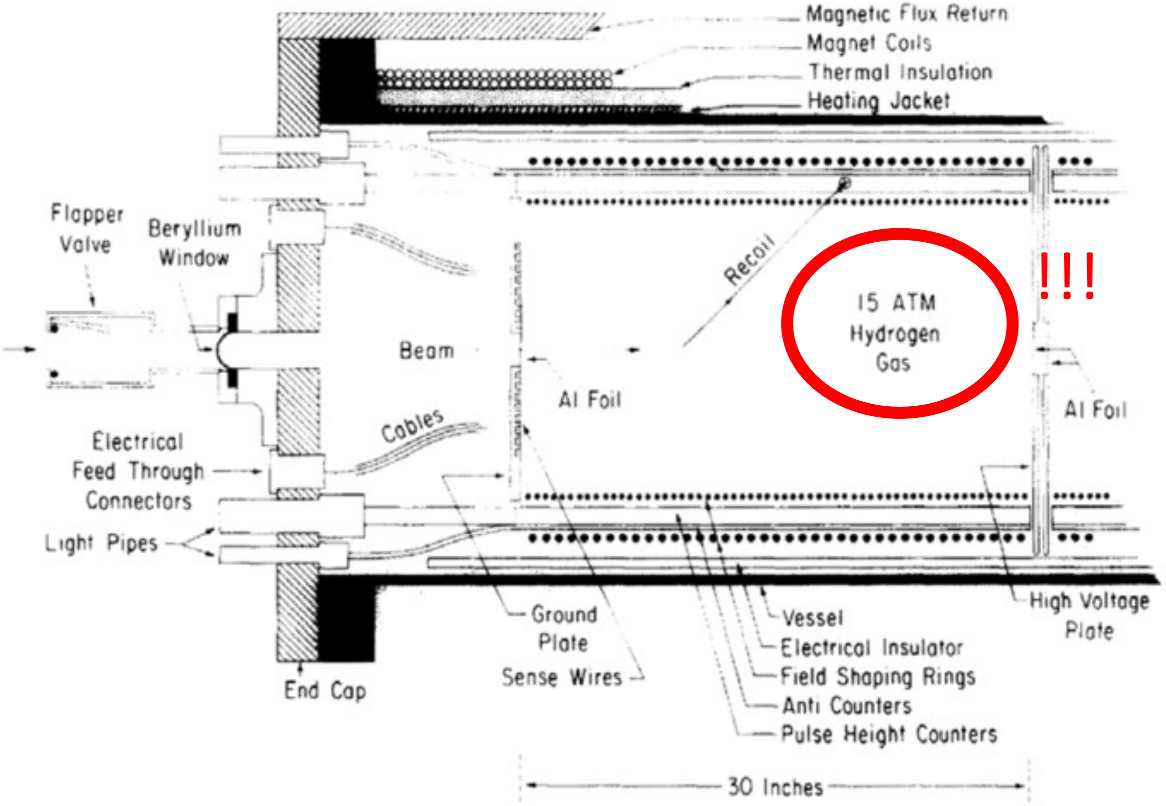


~2000 SensL 1-mm² SiPMs

A. Bross

E-612 at Fermilab (active target + spectrometer)

- Study of photon diffraction dissociation on hydrogen.
  - γ +p ➛ X +p
  - Active target TPC consisting of two identical 75 cm long by 45 cm diameter drift regions filled with H_2 at 15 bar.
  - B = 1kG



1984

Fermilab

Credit: K. Mavrokoridis, Liverpool

2D -> Full 3D Optical Readout

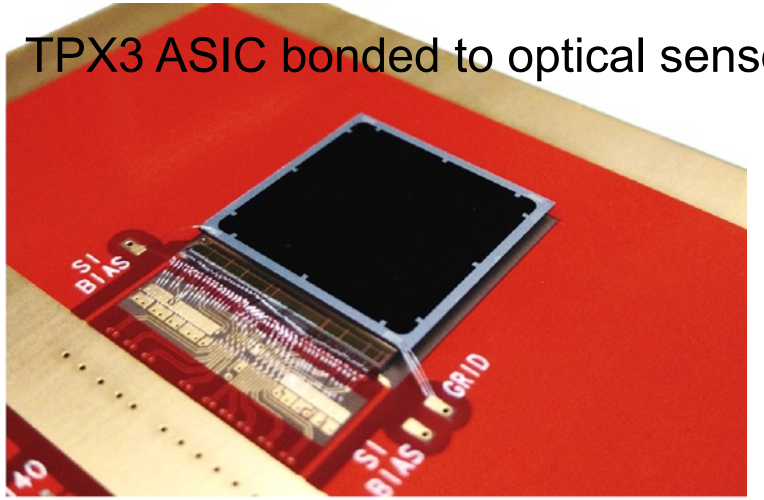
Silicon pixel readout chip developed by the Medipix collaboration. **Very well established** technology at CERN.

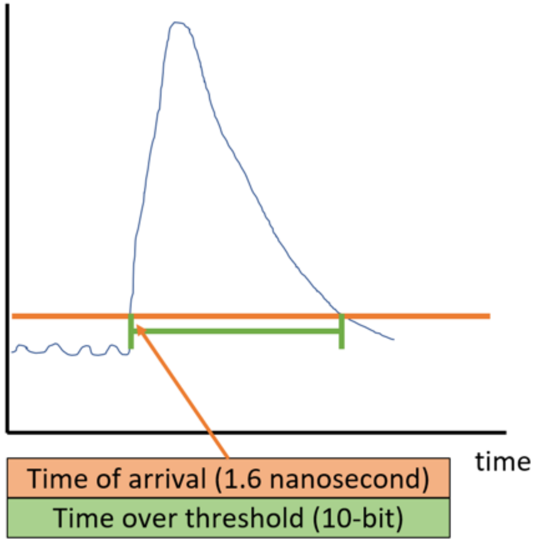
TPX3 provides simultaneous time-over-threshold (ToT) and time-of-arrival (ToA). **Complete (x,y,z,E) event reconstruction using a single device.**

Time over threshold provides intensity / energy measurement ->10-bit resolution.

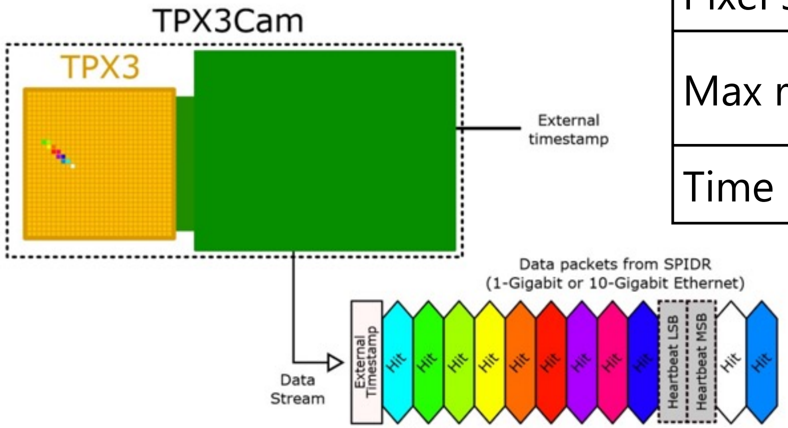
Time of arrival provides z (drift) axis position information -> 1.6 nanosecond resolution.

Data driven readout -> Event streaming with native zero suppression.
Efficient raw data storage. Triggerless operation.





Sensor resolution	256x256 pixels
Pixel size	55μm x 55μm
Max readout rate	40Mhits•cm^{-2} •sec^{-1}
Time resolution	1.6 ns



Liquid vs. Gas

- Drift velocity in LAr at E = ~500 V/cm: 1.6 mm/us
- For a gaseous argon-based TPC, using pure argon is not easy for detector HV stability reasons
  - Usually need some fraction of molecular additive (CH_4,CO_2, CF_4, etc) to quench primary scintillation (which causes feedback/instability via photoelectric effect) which also often has the benefit of increasing drift velocity to ~1-10 **cm**/us
- Spatial resolution
  - Existing 3mm wire pitch LArTPCs achieve ~1mm resolution
  - Existing gaseous TPCs achieve ~100's um resolution
  - Diffusion of drifting electron cloud affects spatial resolution